

EPB tunneling challenges in bouldery ground: a new experience on the Tabriz metro line 1, Iran

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Abstract Underground construction of the Tabriz metro line 1 involved boring twin tunnels with two earth pressure balance machines in alluvial deposits. Although this type of machine is recommended for excavation in fine soils, its performance was evaluated in this project where part of the ground consists of alluvial deposits with particle size ranging from silt to boulder and even rock blocks. It was found that the tunnel boring machine (TBM) performance was highly reduced due to the variation in ground conditions. Many types of problem were observed during the excavation in coarse grained alluvial deposits including high cutter-head torque, excessive wear of tools, breaking of TBM parts and ground instabilities in the form of large settlement and ground collapse. A trial effort was implanted to stabilize the overburden ground by the injection of cement grout, but this proved to be unsuccessful. In both cases, the excavation operation was delayed. With the experience gained from the excavation of the first tunnel and use of foam with a high foam expansion ratio as a soil conditioner in closed mode, the performance of the TBM in the second tunnel improved.

Keywords Tabriz metro line 1 · EPB TBM tunneling · Bouldery ground · Soil conditioning

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Introduction

Application of full-face tunnel boring machines has recently been increased for construction of underground projects in urban cities. To select a suitable machine for a certain project, local information including site geology, tunnel alignment, site restrictions and ground water conditions is required. According to Skiegedal and Holter (1998), favorable geological conditions for a selected tunnel boring machine (TBM) machine make the tunneling better than the conventional excavation method, with reduction in overall construction time and cost savings.

The subject of tunneling in urban area has been considered by many researchers in recent years. For example, Noppadol et al. (2006) considered the characteristics of ground movement from shield tunneling of the first Bangkok Subway line. Zhao et al. (2006) studied the effect of frequently changing and mixed ground on tunneling in Singapore. Centis and Giacomini (2004) investigated the performance of earth pressure balance (EPB) tunneling in highly variable ground. Carrieri et al. (2006) evaluated the application of an EPB boring machine in very coarse grained deposits along the Torino metro line 1.

In this paper, the performance of EPB for construction of the Tabriz metro in mixed ground conditions is discussed. The types of problem encountered during tunneling are reviewed, and some suggestions for advancing the boring operation are given.

Project specifications

Line 1 of Tabriz metro project is part of metropolitan transportation development of Tabriz city. The city with a population of around 1,400,000 is located in northwest Iran and it is the capital of East Azerbaijan Province. The project is 16 km

long of which 8.5 km includes a twin tunnel with finished internal diameters of 6 m. This line consists of 11 underground stations and passes underneath the historical city centre, as well as a number of important archaeological sites including the Kaboud Mosque (approximately 300 years old). The general layout of Tabriz metro network is shown in Fig. 1.

Two EPB tunneling machines of 6.88 m diameter are in use for construction of the twin tunnels. The rotating cutter-head of the EPB machine is equipped with five types of excavation tools which include ripper, bucket, scraper, cutter discs and protection bites. A screw conveyor extracts the soil from the head chamber, allowing control of the volume of soil evacuated by the machine to balance the earth pressure in the head chamber. By this process, the pressurized head chamber supports the ground during excavation to provide stability and minimum ground movements. Segmental precast concrete with internal diameter of 6 m, 1.4 m in width and 0.3 m in thickness is used as permanent ground support (see Fig. 2).



Fig. 2 Full-face view of TBMs used in the excavation of Tabriz metro line 1

Geological setting

Geological setting of Tabriz city mainly consists of a series of sedimentary rocks, pyroclastic deposits of volcanic

origin and young alluvial deposits. The sedimentary rocks include laminated layers of sandstone, mudstone and marl and thin layers of gypsum. These units are locally known as the Upper Red Formation, and according to Hessami et al. (2003), they were deposited in an Upper Miocene to Pliocene basin during a time of intense tectonics and

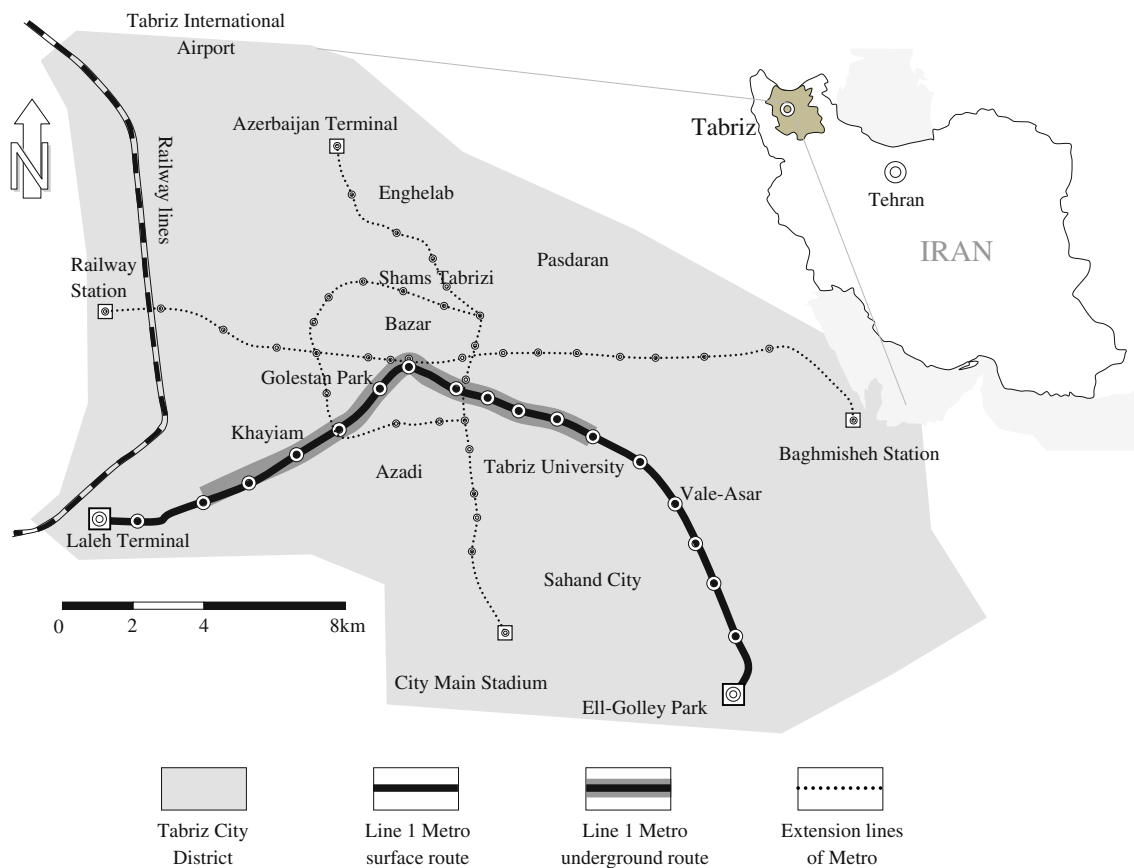


Fig. 1 General layout of Tabriz metro network

volcanism. The sedimentary units cover most parts of north Tabriz city. Pyroclastic deposits consist of intrusive igneous rock fragments such as andesite and tuffaceous conglomerate and agglomerate breccia of volcanic origin. These units are dated back to the Eocene and are the result of Sahand Volcano activities. The pyroclastic deposits have wide outcrop to the southeast parts of the city. The alluvial deposits are accumulated along the flowing stream and river beds of two main rivers named Aji-Chai and Mehran-Rood which drain the region into Uromia Lake in the eastern part of the city. The geological map of the region is illustrated in Fig. 3.

Engineering geological properties

The engineering geological properties of the alluvial deposits were evaluated by conducting a series of in situ tests including SPT and permeability tests in a number of boreholes. The boreholes were drilled at an average 200 m spacing along the tunnel line. Also, samples were taken to laboratories for the determination of shear strength and soil grain size distribution. The summary of the test results is

shown in Table 1. The results show that the soil types are mainly classified as SM but, during field observation, there were some local accumulations and lenses of larger fragments of fresh to slightly weathered andesite. The uniaxial compression strength of these fragments is in the range of 50–80 MPa, and their presence affects adversely on the operation of the TBM during excavation. According to the SPT values, the soils are dense and the range of natural density varies between 1.6 and 2.1 gr/cm³. The groundwater table in the section of this study is 3–8 m below the tunnel alignment. According to the results of in situ permeability tests along the tunnel alignment, the coefficient of permeability was in the range of 10⁻⁶–10⁻⁹ m/s. Figure 4 shows the location of boreholes and soil layers along the entrance of metro tunnel.

Engineering geological problems in the Tabriz metro

The first part of tunneling operations along the Tabriz metro line 1 faced two types of problem. The problems are directly related to the geological setting of the site. They can be described as follows:

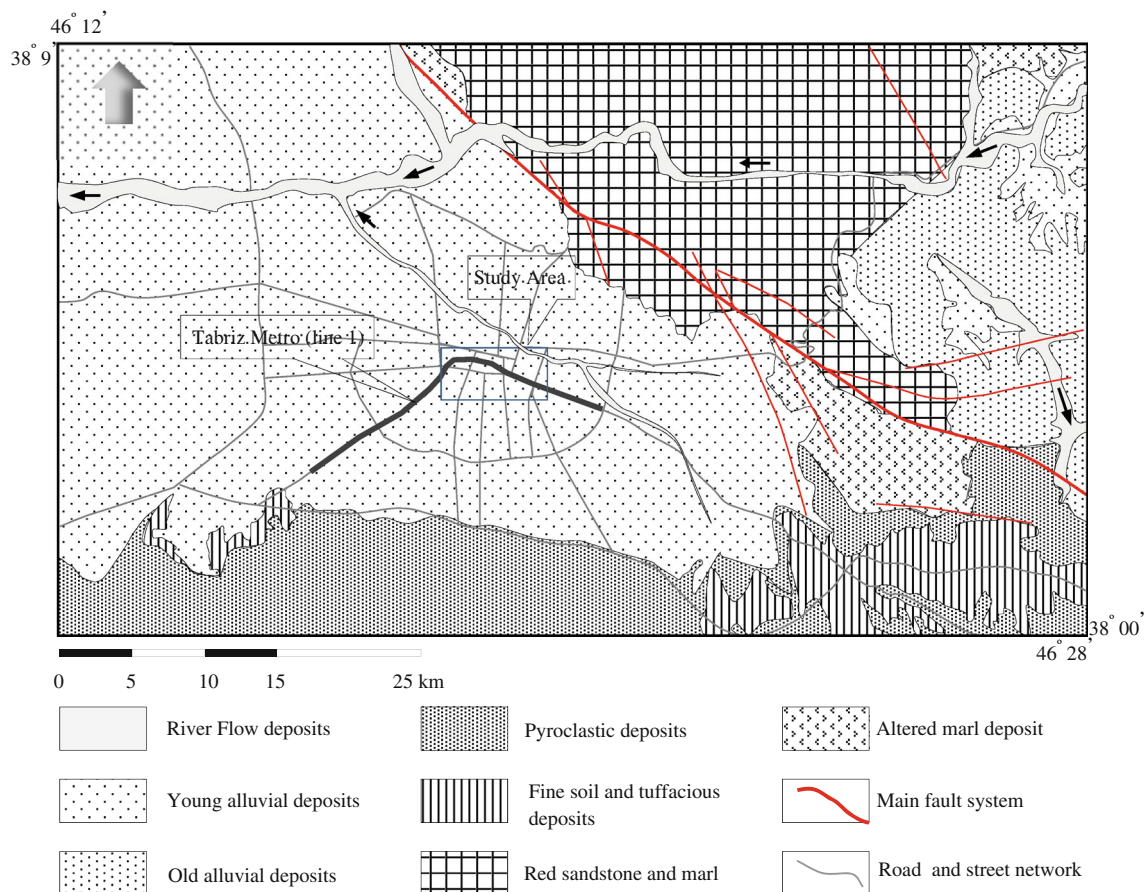


Fig. 3 Geological setting of Tabriz city area

Tunnel face instability

Hard driving conditions were experienced in the first 700 m of the tunnel entrance, due to the presence of rock fragments and boulders within the alluvial deposits. The main problems in terms of face instability included damage to the cutter-heads and a high rate of abrasiveness to the wearing parts. The other problem at this stage of boring was the small thickness of the overburden which caused collapse at the ground surface along the tunnel route due to the generated vibration.

Because of their size, rock blocks were too large to transfer from the cutting face into the head chamber and extract via the screw conveyor, which had a diameter of 0.9 m. Therefore, the accumulation of boulders and rock blocks in the chamber and in front of the cutter-head and,

Table 1 Summary of test results of soil in three boreholes location

Borehole no.	Distance (m)	Soil type (unified)	SPT (N)	\emptyset (°)	C (kPa)
FBH-1	6 + 835	SM, SP-SM	>50	36.5	14.5
MBH-5	7 + 040	SM	>50	–	–
FBH-2	7 + 171	SM	>50	36	0

simultaneously, movement of them between the cutter-head and the tunnel face caused high torque of the cutter-head relative to other parts of the tunnel alignment composed of finer soil particles, reduced the performance of the machine boring operation and created a disturbed zone about 0.4 m from the tunnel face. Figure 5 shows the variation in cutter-head torque in different geologies, which were recorded by the data acquisition system of the TBM, and Fig. 6 shows the front of the cutter-head and the interaction between boulders and cutter discs.

Movement and rotation of boulders caused trembling and vibration in the ground; this situation consequently led to instability of the tunnel face and regular occurrences of ground collapse. Figure 7 shows an example of ground collapse in a street.

In the case of Tabriz metro, the alluvial deposits were classified into three levels of compaction which can be identified as follows;

1. Low compacted deposits: boulders rotate simultaneously with the cutter-head which causes their separation from the tunnel face.
2. Medium compacted deposits: boulders pushed into the tunnel face by the pressure of the cutter-head

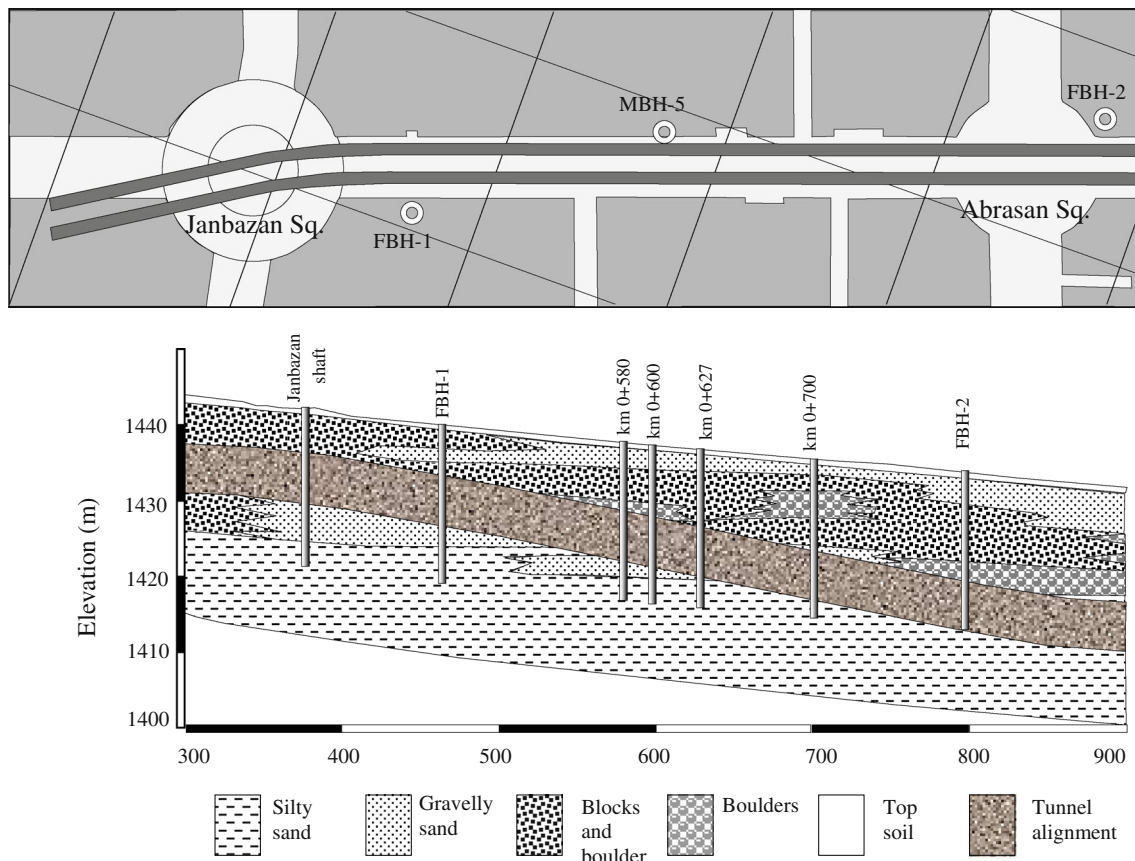


Fig. 4 Location of boreholes and type of soil layers at the entrance of tunnel alignment

Fig. 5 TBM torque and thrust in different soil layers

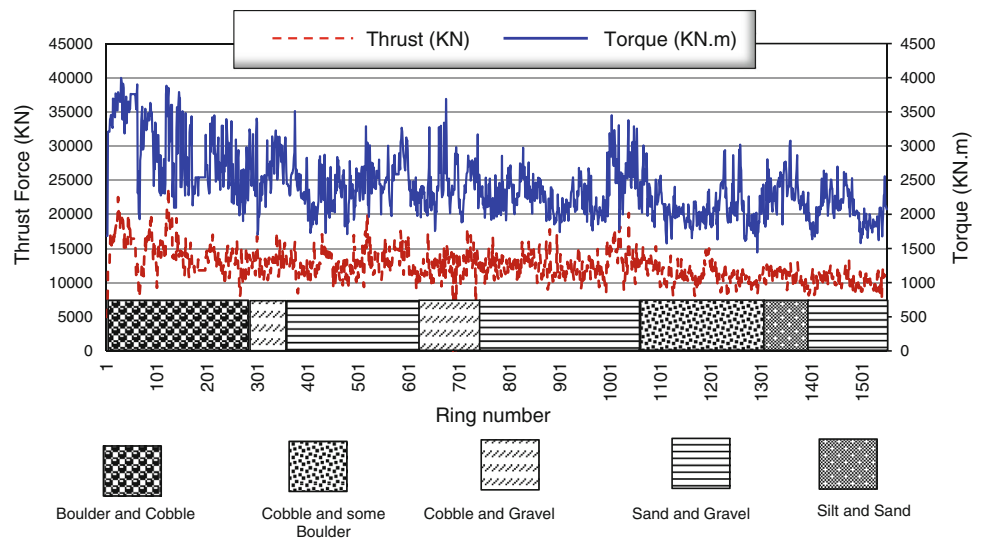


Fig. 6 Distance of cutter-head from the tunnel face

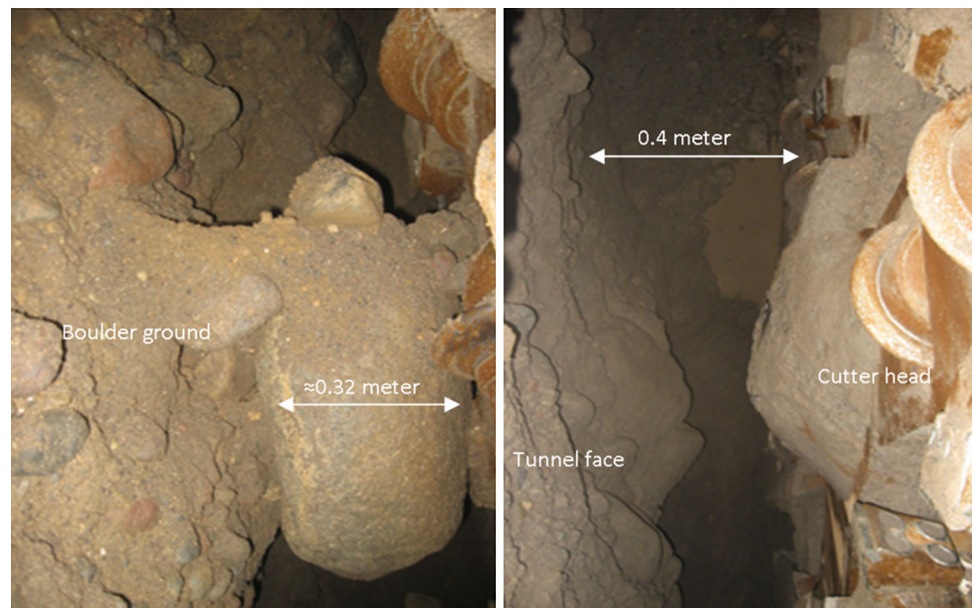


Fig. 7 Tunnel face instability and ground collapse

- consequently causing a gradual increase in ground density and harder boring effort.
- Highly compacted deposits: boulders are broken by the effect of the cutter-head, which causes the generation of higher ground vibration and more damage to the wearing parts.

Interaction between the cutter-head and the ground depends on the effect of ground compaction on the performance of the TBM is shown on Fig. 8.

Damage to TBM parts and excessive wear of tools

For an effective EPB operation and reduction in ground movement and surface settlement, it is necessary to keep

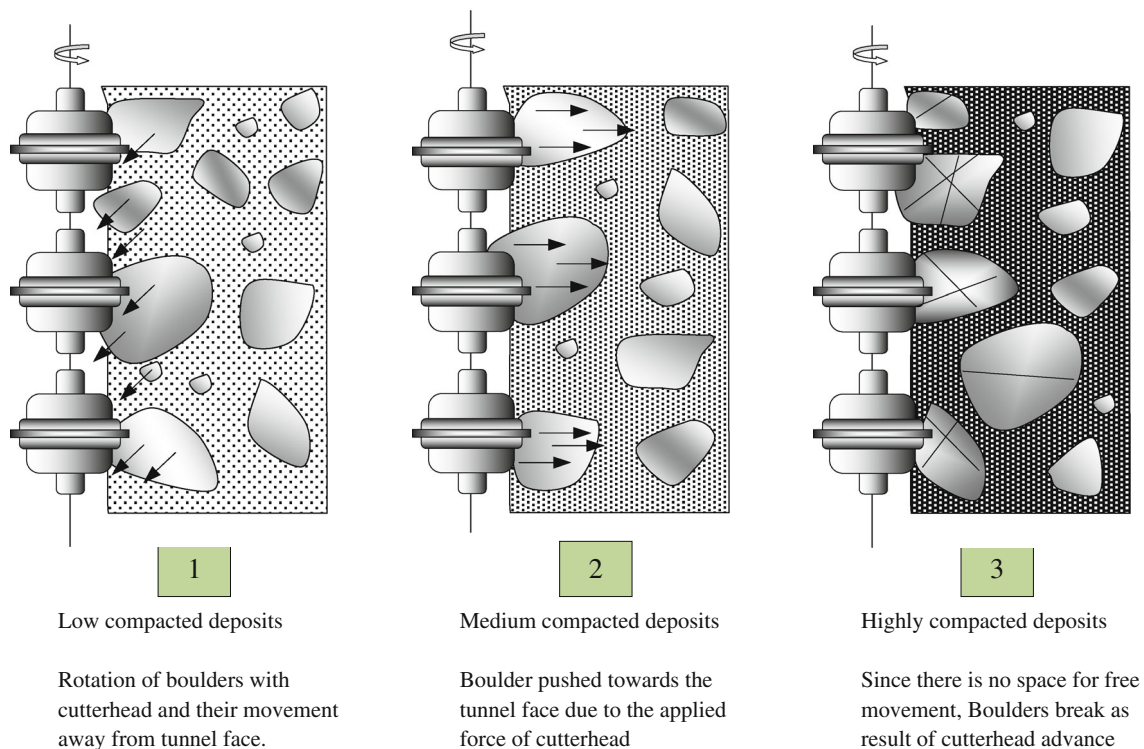


Fig. 8 Interaction between cutting discs and ground (excavation mechanism) in different level of granular ground compaction

the excavation chamber full of dense material to have tunnel face support pressure balance. The rotation of the cutter-head depending on the geological setting of the site results in cutter-head torque, excessive damage and wear of TBM parts and, subsequently, in some cases, locking of the screw conveyor.

Another factor that controls the EPB operation is the degree of ground abrasivity. The abrasivity of the rock fragments within the soil is controlled by the type of mineral content and its hardness, whereas in soils, other factors influence the abrasivity including soil homogeneity, density, porosity, water content and soil strength regarding their friction angle and cohesion.

Abrasivity assessment of soil samples

The cutting tool's life and the level of damage to the TBM parts can be estimated from the relative percentages of minerals with different hardnesses. For coarse-grained soil, this can be determined by petrographic analysis using a microscope. Figure 9 shows the petrographic study of thin sections of soil samples under the microscope. Abrasivity is mainly affected by various factors such as mineral composition, the hardness of mineral constituents and grain characteristics. To include all minerals of a soil sample, the equivalent quartz content has to be determined in thin sections, meaning that the entire mineral content is

referenced to the abrasiveness or hardness of quartz (Eq. 1). Therefore, each mineral amount is multiplied its relative Rosiwal abrasivity of quartz (with quartz being 100) (Thuro 1997).

$$\text{equ} = \sum_{i=1}^n A_i \times R_i, \quad (1)$$

where A_i is mineral amount (%), R_i is Rosiwal abrasiveness (%), and n is the number of different minerals. The types and the mineral contents of soils along the relevant part of Tabriz metro line 1, mineralogical content hardness and equivalent quartz content (EQC) are given in Table 2.

It can be seen that the total Rosiwal hardness of the soil is around 60 % and most of the soil components are formed by particles with high hardnesses.

To measure abrasivity, two standard tests (LCPC and Cerchar tests) were carried out on soil and rock fragments, respectively.

The abrasivity test of the Laboratoire Central des Ponts et Chaussées (LCPC) (normalized according to AFNOR NF P94-430-2) consists of measuring the weight loss of a steel plate rotating at 4,500 rpm for 5 min in 500 g of crushed rock or soil samples, which was previously sieved and prepared at 4–6.3 mm diameter. The abrasivity coefficient, ABR, is defined as the ratio of the plate's weight loss to the mass of tested material (see Fig. 10). The index is given in grams per ton and varies between 0 and over 2,000 depending on sample

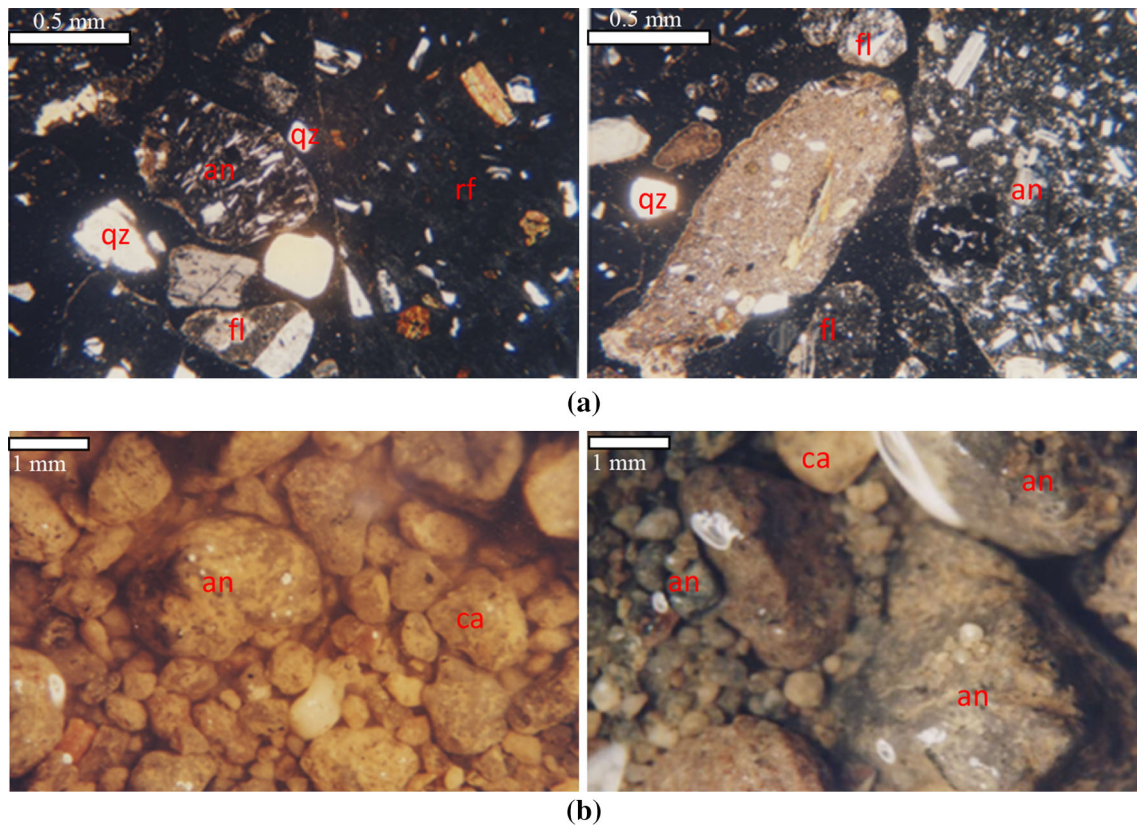


Fig. 9 **a** Microscopic and **b** Morphoscopic images of soil samples **a left** volcanic rock fragments (rf) with quartz (qz) and feldspar (fl) crystals; **right** volcanic rock fragments (rf) such as andesite (an) with quartz (qz), feldspar and plagioclase (fl) minerals, **b left** subrounded

to rounded volcanic rock fragments with quartz, feldspar crystals and some carbonates (ca) content **right** subrounded volcanic and some carbonate rock fragments with crystal content

Table 2 Mineralogy and hardness of soil particles

Mineral component	Particle shapes	Frequency (%)	Moh's hardness	Rosiwal hardness	Rosiwal hardness × frequency
Igneous rock fragment (andesite)	Subrounded to rounded	75	6.5	65	48.75
Crystalline minerals, biotite, amphibolite, feldspars	Subrounded to rounded	10	5.2	18	1.8
Arenite (quartz sand)	Angular to subrounded	10	7.0	100	10
Carbonates fragments (calcite and dolomite)	Rounded	3	2.5	1.5	0.045
Soil matrix (silt and clay)	Rounded	2	2.5	1.5	0.03
Total Rosiwal hardness					61.03

abrasivity. Test results on the Tabriz metro line 1 soil sample with particle size between 2.0 and 6.3 mm are given in Table 3. The test result showed LCPC abrasivity coefficient to be around 620 g/t.

In the Cerchar test, a sharp steel indenter (hardness of 200 kg/mm²) of 90° cone angle is applied to the surface of a rock specimen with a static force of 70 N. The steel point is then slowly moved on 10 mm. This procedure is repeated five times in various directions on the rock surface, always using a fresh steel tip.

The abrasivity of the soil containing rock fragments is obtained by measuring with a microscope the resulting

wear flat on the steel cone. The unit of abrasivity is defined as a wear flat of 0.1 mm diameter. The test results showed respective CAI mean values for rock fragments of 2.5–4.5. On the basis of these parameters (quartz content percent, LCPC and Cerchar test results) and considering the charts illustrated in Figs. 11, 12, the abrasivity of soil was evaluated as being very abrasive.

This results in a high rate of abrasivity of the tool parts especially for the flat cutter ring. Due to the lack of a rolling force for the cutter-head to overcome the pre-torque effect, the rotation of the cutter discs was stopped. Figure 13 shows different types of damage to the wear parts of the cutter-head.

Fig. 10 LCPC testing device and its impellers. *a* Before test, *b* after test of the Tabriz metro line 1 soil sample

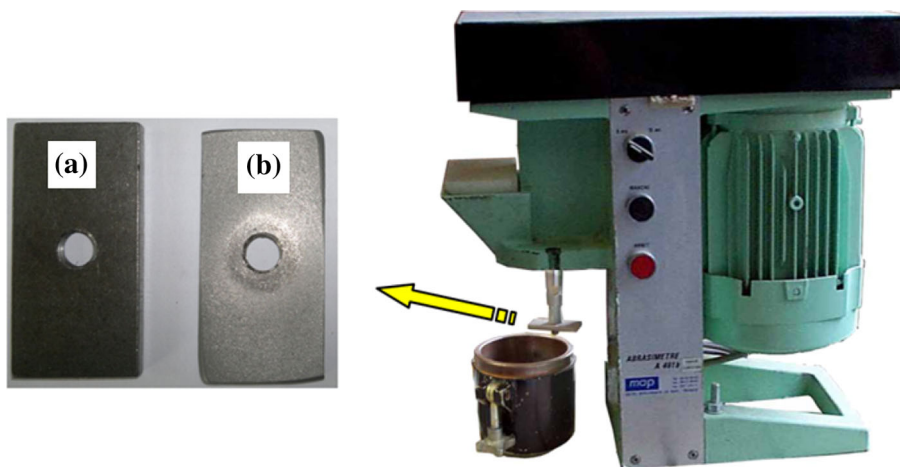


Table 3 LCPC test result of the Tabriz metro line 1 soil sample

Impeller weight before the test (gr)	Impeller weight after the test (gr)	Impeller weight loss (mgr)	LCPC abrasivity coefficient (LAC)	Abrasivity of soil
46,749	46,439	310	620	Very abrasive

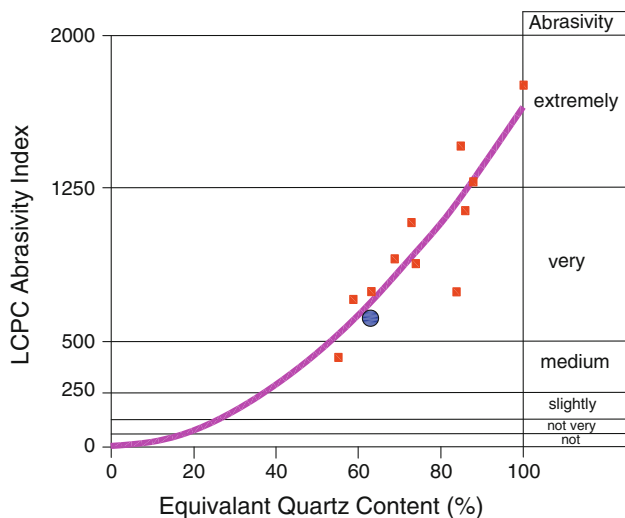


Fig. 11 Correlation between LAC and equivalent quartz content (Festl 2006) and the position of the Tabriz metro line 1 sample on this chart

Ground treatment

To improve the ground stability ahead of the driving operation, it was decided to treat the overburden soil above the tunnel alignment by cement grouting. The initial grouting operation involved drilling 24 boreholes in 3 rows at

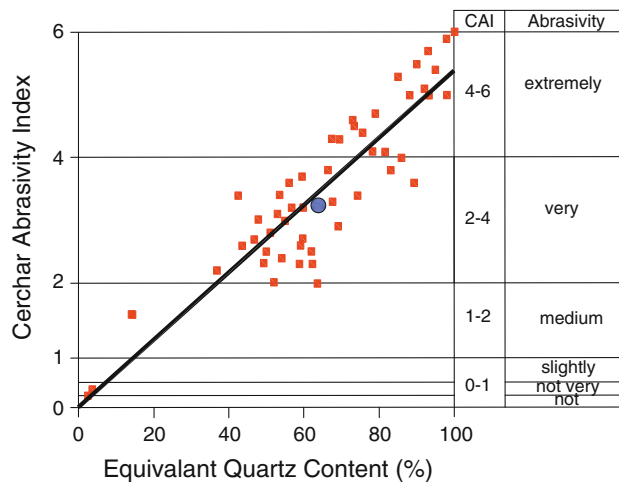


Fig. 12 Relation between CAI and equivalent quartz content (Thuro and Käsling 2009) and the position of the Tabriz metro line 1 sample on this chart

1.5 m spacing and at a distance of 3.5 m from the cutter-head position in the tunnel. The boreholes were drilled from the ground surface using the tube-manchette technique for grout injection. The technique consists of a pipe with rubber jackets covering small grout holes equally spaced along the pipe. The jackets act as check valves that permit the grout to flow only out of the pipe (Ewert 1985).



Fig. 13 Damage of TBM parts and excessive wear of tools. **a** Breakage of cutter tools due to boulder interaction, **b** flat wear of cutter disc, **c** wear of bucket tool

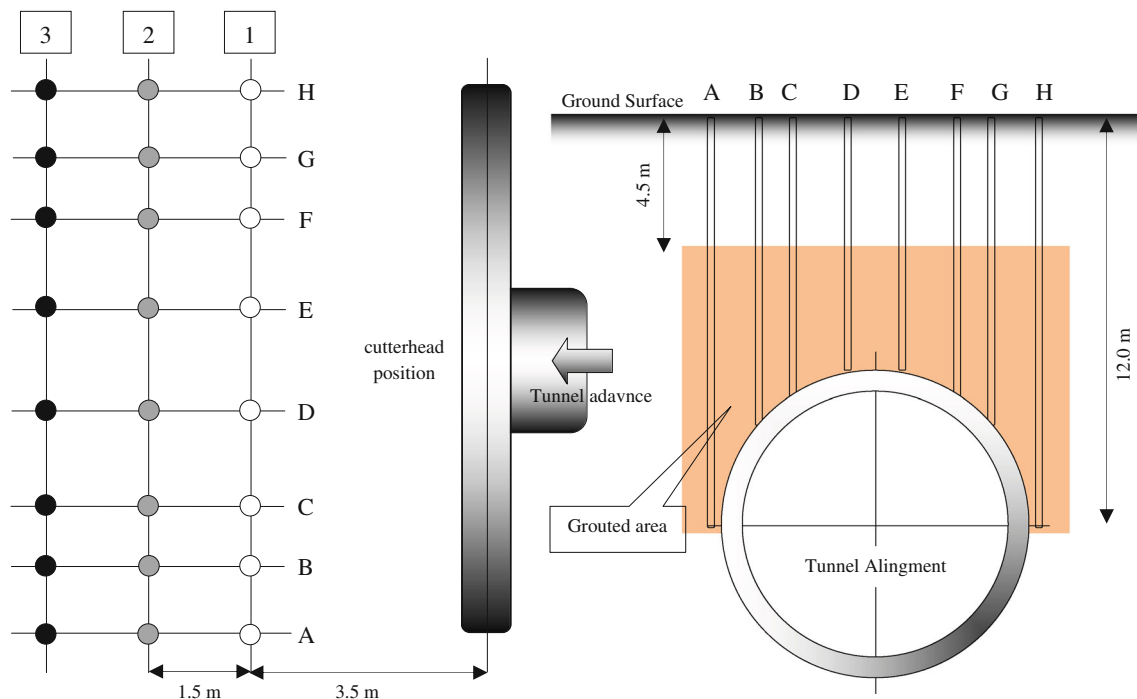


Fig. 14 Alignment of grout boreholes around the face of tunnel

The injection pressure varied from 1.0 to 6.0 bars. To prevent damage to the surrounding substructures, the depth of grouting started at 4 m from the ground surface and covered the upper parts of the tunnel alignment. The layout of boreholes and the tunnel alignment are shown in Fig. 14. The grout material mainly consisted of a mixture of cement and water (ratio 3:1) and some minor additives of bentonite and sand.

Results of the grouting activities are plotted in Fig. 15 in which the amount of cement intake for each borehole is shown. The volume of grout intake is sharply varied, and there is no defined pattern. This reflects the nature of alluvial soil with different grain size distribution, structure pattern and permeability features.

The effect of grouting on ground improvement was then observed at the location of the cutter-head of the TBM. The observations indicated that the grouting in coarse-grained soil performed very well by penetrating through the large voids and act as a penetrating grout as shown in Fig. 16a. But in fine grained soil, the grout materials were not able to penetrate through the soil. Instead, they formed grout blocks by fracturing the soil structure and acting as a soil fracturing mechanism (see Fig. 16b). The formation of grout blocks (man-made boulders) causes a multiple challenge for the TBM operation. The cutter-head of the TBM was blocked when it encountered these massive cement blocks. Figure 17a shows massive cement (man-made blocks) in front of the TBM. A pneumatic hammer was used to break the blocks

Fig. 15 Amount of cement intake (kg) in driven boreholes

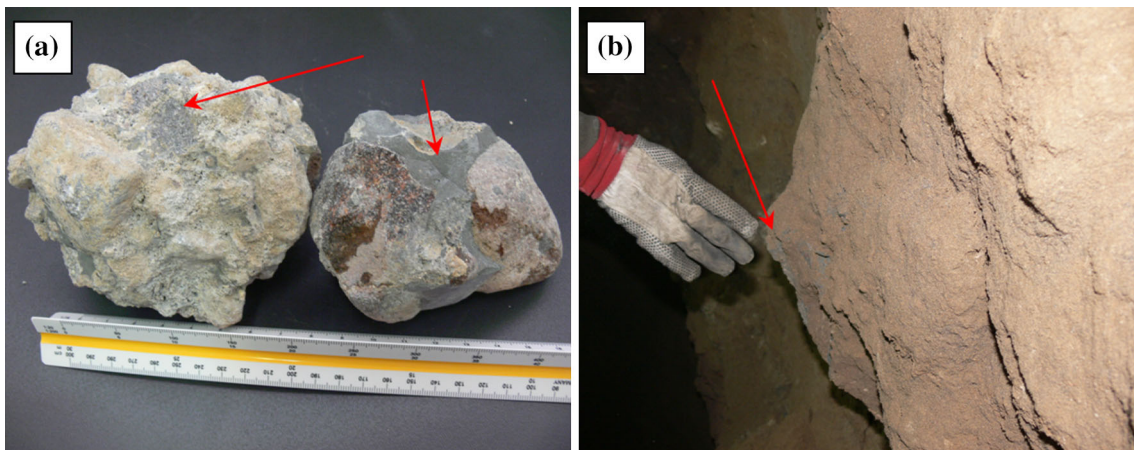
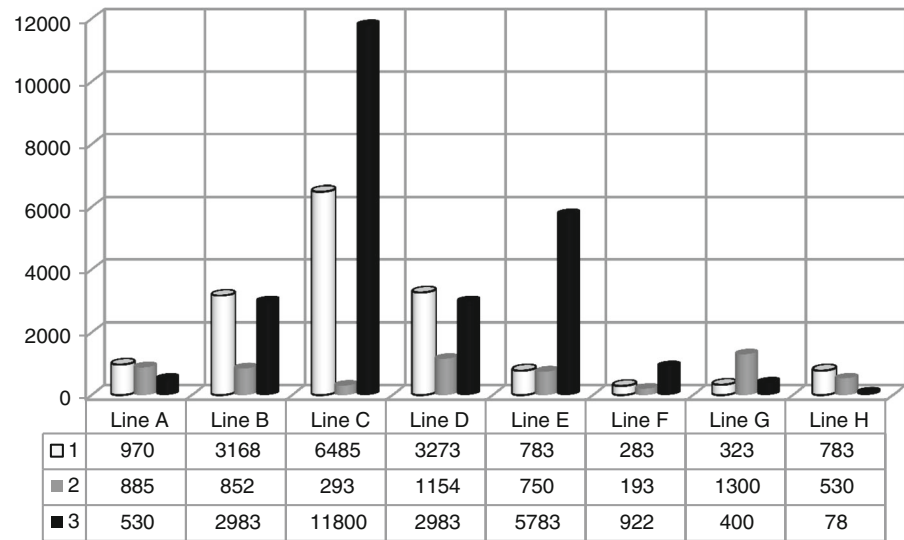


Fig. 16 Ground treatment results on different soil layers. **a** Permeation of grout into the granular soil and **b** forming the blocks (massive cement) into the fine-grained material via soil fracturing

Fig. 17 Encounter of the TBM with cement blocks (man-made boulders) due to grouting
(a) massive cement block in front of the TBM
(b) use of pneumatic hammer for breaking of the cement blocks and removal by hand

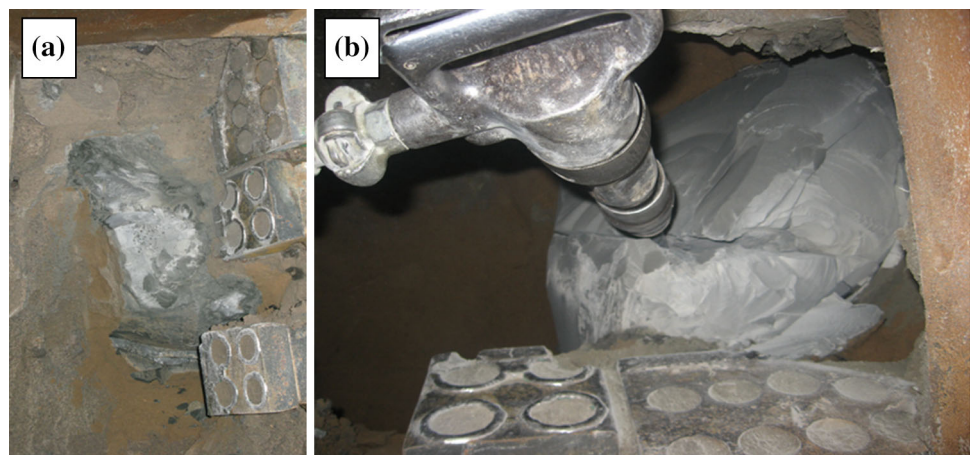




Fig. 18 Tabriz metro line 1 twin tunnels

(Fig. 17b). Therefore, this technique for ground improvement is not recommended for similar projects elsewhere (Fig. 17b).

EPB machine performance

As mentioned previously, the Tabriz metro line 1 includes two parallel twin tunnels under construction by use of two EPB-TBMs (Fig. 18). The performance of the first TBM (Sahand) along the northern tunnel in the starting section in bouldery ground was evaluated regarding the number of rings used to support the excavation for 1 year of operation. It is reminded that each ring be composed of 6 segments with a 1.4 m width and the number of rings used shows the distance of excavation. Plots of the number of rings for 12-months of operation of the TBM are shown in Fig. 19. It can be noted that a total of 340 rings were used

Fig. 19 Performance of first EPB TBM (Sahand) in the Tabriz metro line 1 project in 1 year of operation

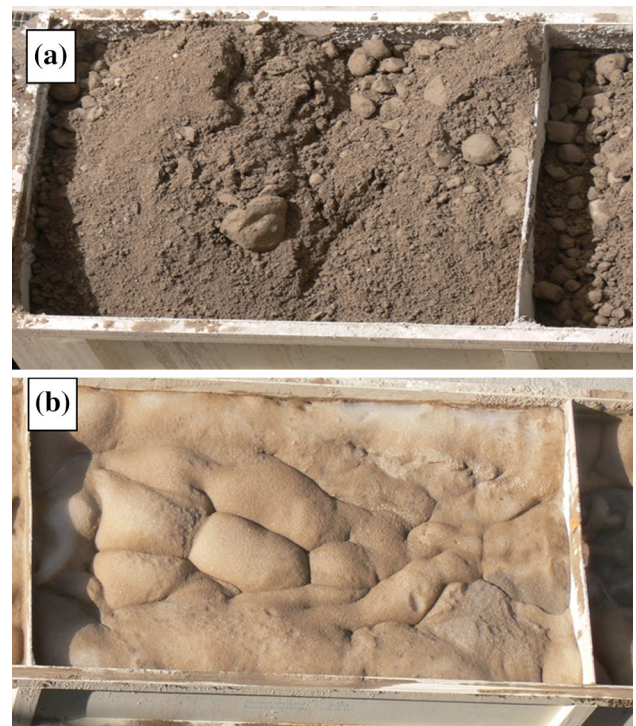
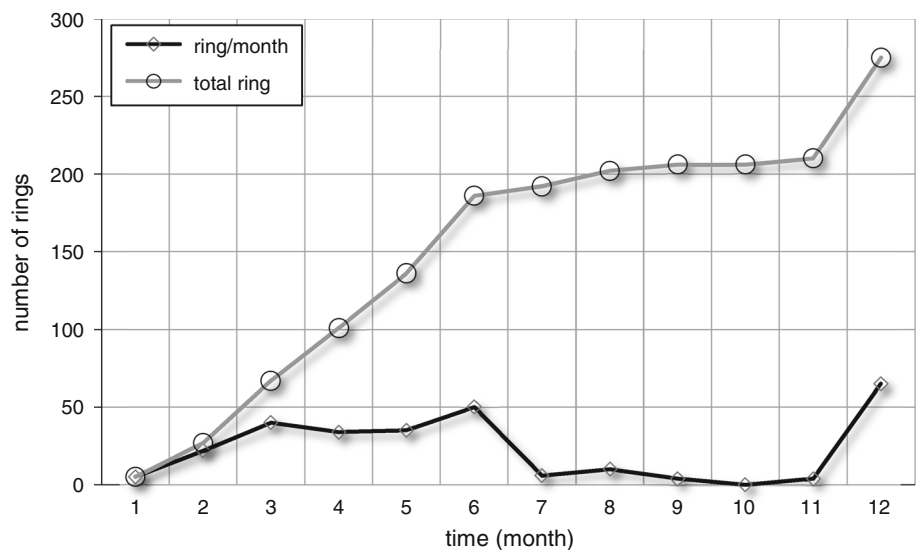
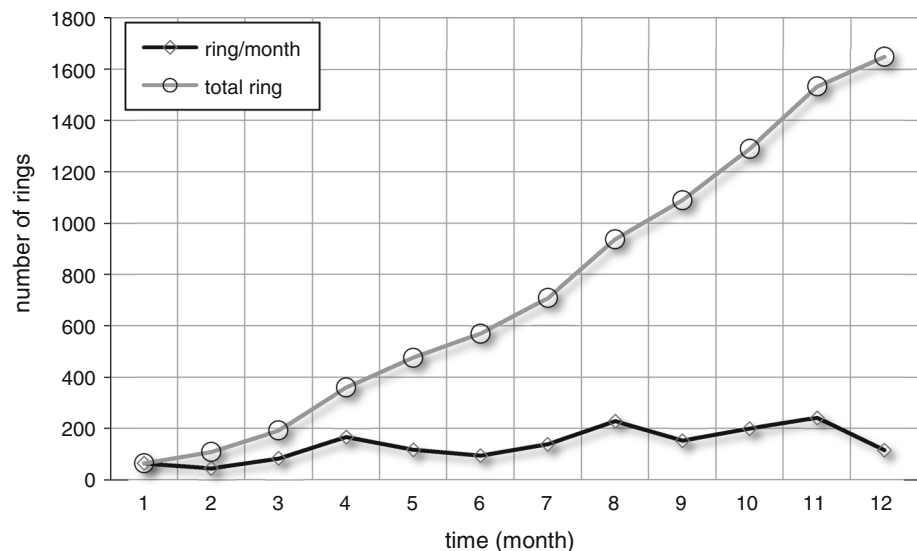


Fig. 20 Use of foam for soil conditioning. **a** Foam with a low FER (<8) in the first TBM and **b** foam with a high FER (>12) in the second TBM

for tunneling progress of the TBM in the first year in coarse and bouldery ground conditions. The overall performance of the boring machine was almost just one ring per day.

With the experience gained from the excavation of the first tunnel, the excavation of the second tunnel (Sabalan) was started at a distance equal to just 6.5 m from the first in the same ground. In this tunnel, instead of ground treatment and removal of boulders manually, foam with a high foam

Fig. 21 Performance of second EPB TBM (Sabalan) in the Tabriz metro line 1 project in 1 year of operation



expansion ratio (FER) (see Fig. 20), bentonite for soil conditioning with full head chamber and earth pressure balance around 30 Kpa (closed mode) were applied. The result was tunneling without collapse and with authorized settlement and high TBM performance. Figure 21 illustrates the second TBM performance in its first year. As it can be seen that 359 rings in this tunnel were excavated during 4 months, it means the increasing of TBM performance from 1 to 3 rings/day.

Conclusion

Adequate geological investigation of a tunnel route is essential for the selection and design of a suitable TBM. Since variable ground conditions exist along the route of a tunnel, the boring machine should be modified to fulfill the requirement of a given site. Although the EPB type of boring machine is recommended for fine-grained soils, the machine was used to excavate the twin tunnel for the Tabriz metro line 1 where a mixture of particles with very varying grain sizes are present within the alluvial deposits.

Abrasivity assessment of the Tabriz metro line 1 soil composition by petrographical study and estimation of equivalent quartz content, LCPC abrasivity test and Cerchar test confirmed the high abrasivity of ground material.

A trial was used to modify the ground by grout injection, but results showed that treating the overburden deposits by cement grouting is not a suitable method unless bentonite is used to reduce the ability of the grout to damage the TBM.

In other places with similar ground problems, instead of ground treatment by cement grouting, it is recommend to use suitable additives such as polymeric foam and bentonite as a soil conditioning and to keep the head chamber full of material to have earth pressure balance

(closed mode). The TBM should be advanced slowly to reduce trembling and vibration of the ground.

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